Use of Statistical Tools to Improve Modeling and Simulation of Store Separation

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ABSTRACT

The MK-82 Joint Direct Attack Munition (GBU-38) is cleared for carriage and employment for the entire F/A-18C aircraft flight envelop from the BRU-55 Canted Vertical Ejector Rack (CVER). The GBU-38 was certified for carriage and release through a series of flight tests. For the first flight where the store was released from the BRU-55, the wind tunnel Captive Trajectory System (CTS) data, as well as NAVAIR and Boeing pre-flight predictions, showed no resemblance to the flight test results.

The original NAVSEP and Boeing predictions considerably underpredicted the roll rate, and had the yaw rates in the opposite direction from the flight test telemetry results. Since the wind tunnel CTS trajectories had the same errors, the simulations obviously were missing an important feature of the trajectories. For the flight from the CVER there was a spike in the rolling moment during the ejector stroke. This roll spike was attributed to the misalignment between the ejector force line of action and the store c.g. A statistical approach was used to modify the ejector force characteristics to best match the flight test data. This modification gave an excellent match with the flight test results for all the succeeding test points.

1.0 NOMENCLATURE

BL: Aircraft Buttline, positive outboard, in.
C_l: Rolling moment coefficient, positive rt wing down
C_m: Pitching moment coefficient, positive up
C_N: Normal Force coefficient, positive up
C_n: Yawing moment coefficient, positive nose right
C_p: Pressure Coefficient
C_Y: Side force coefficient, positive right
FEJ: Total Ejector Force, lbs.
FZ1: Forward Ejector Force, lbs.
FZ2: Aft Ejector Force, lbs.
FS: Aircraft Fuselage Station, positive aft, in.
M: Mach number
NAVSEP: Navy Generalized Separation Package
P: Store roll rate, positive rt wing down
Q: Store pitch rate, positive nose up
R: Store yaw rate, positive nose right
XCG: Store CG location, ft. full scale
X1: Distance from store nose to forward ejector foot, ft. full scale
X2: Distance from store nose to aft ejector foot, ft. full scale

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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

X/C: longitudinal displacement divided by wing chord
Z: Store C.G. location, positive down, ft.
α: Angle of attack, deg.
PHI: Store roll angle, positive rt wing down, deg.
PSI: Store yaw angle, positive nose right, deg.
THE: Store pitch angle, positive nose up, deg.
ϕ: CVER line of action, deg.
WL: Aircraft Waterline, positive up, in.
Note: all wind tunnel and flight test data shown are right wing justified

2.0 EJECTOR FORCE EFFECTS

2.1 Original Formulation

The original NAVSEP[1] and Boeing predictions were in excellent agreement with the flight test data for the store ejected from the parent pylon. However, for the flight from the CVER, the predictions considerably underpredicted the roll rate, and had the yaw rates in the opposite direction from the flight test telemetry results, Figure 1. For the CVER flight, there was a spike in the rolling moment during the ejector stroke. This roll spike was attributed to the misalignment between the ejector force line of action and the store c.g. This was modeled as the horizontal component of the ejector force in NAVSEP as:

$$\mathbf{P = \Delta C_l = \sin\phi * F_{EJ} * store\ radius * FACT01}$$

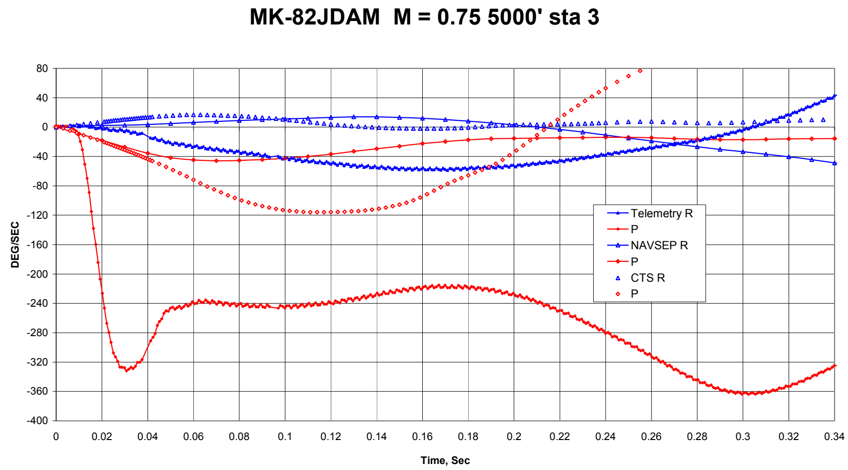

Figure 1

Furthermore, the yaw rate prediction had the wrong sign during the first .06 seconds of the trajectory. Assuming that these effects might be attributable to ejector rack dynamics during the ejector stroke, the NAVSEP code was also changed to match the yaw rates during the first 60 ms:

$$\mathbf{R = \{F_{Z1} * (X_{CG}-X_1)+F_{Z2} * (X_2-X_{CG})\} * FACT02}$$

These modifications considerably improved the trajectory predictions, NAVMOD, Figure 2.

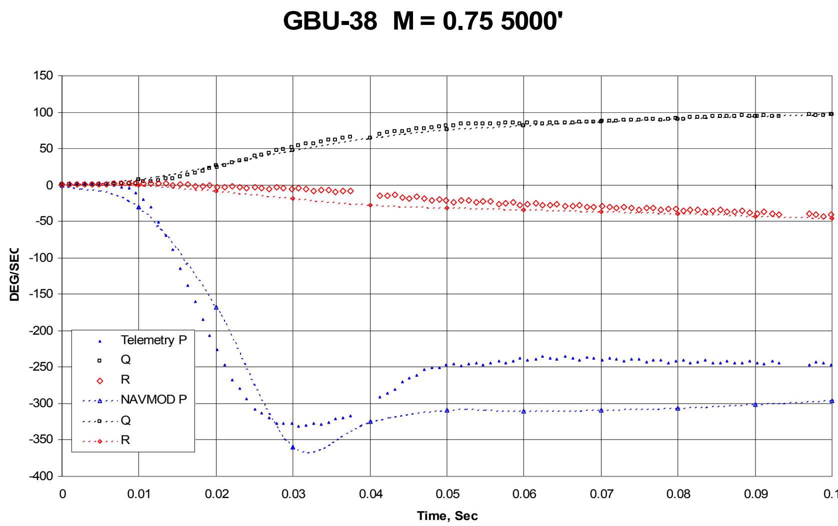

Figure 2

Since the ejector effects were assumed to be independent of Mach number, the NAVSEP program was modified to assign correction factors to the roll and yaw rates during the duration of the ejector stroke. The predicted pitch, yaw and roll rates were compared to the test data in a least squares sense for the first 0.10 seconds. A residual was calculated by adding the square of the differences between the predicted and actual pitch, yaw and roll rates for the first 0.10 seconds of the trajectory. This residual was then used to determine what the values of the factors should be.

Due to the time pressures of the flight test program, these factors, which were determined at M = 0.75, were then applied to all the other test Mach numbers (M = 0.90, 0.95, 1.2), for three different configurations achieving an excellent match with the flight test data[2]. The excellent match between the modified NAVSEP program and the flight test results enabled the elimination of two flights and four store assets (from the original planned 18 flights and 28 stores), at a considerable cost saving to the program.

2.2 Improved Ejector Force Model

Time pressures forced the use of one set of factors throughout the flight test program. However, even though the two factors considerably improved the match between the predictions and flight test data, clearly these factors should be different depending on aircraft configuration (i.e. aircraft weight, load out, adjacent store, pylon location, etc). With these considerations taken into account, it was felt that that a much better match with the flight test results could have been achieved. Furthermore, recently acquired flight test telemetry data for the MK-83 JDAM (GBU-32), where two adjacent stores were released with a .03 sec. interval between releases, the pitch, yaw and roll behavior for the second store were all clearly coupled during the ejector stroke (-.28 <Time < 0), Figure 3, due to ejector motion.

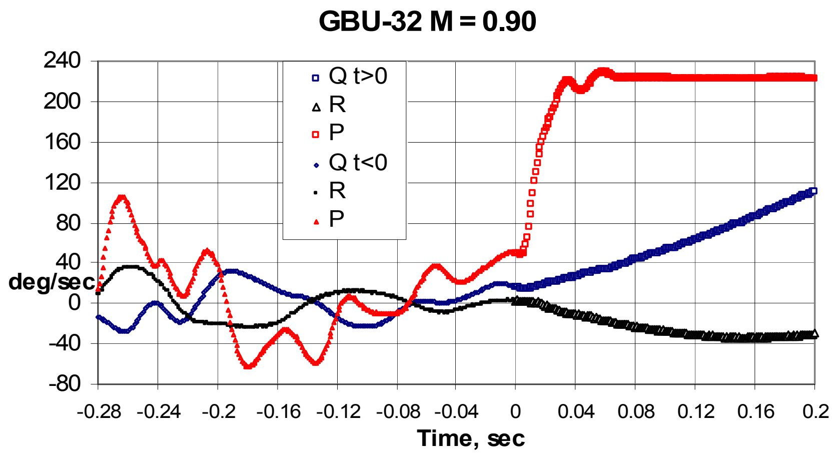

Figure 3

The roll spikes for the GBU-38 differed, depending on whether there was another store on the CVER. Furthermore, the pitch and yaw motion must correspond to the same frequency as the roll. Therefore, six factors, not two are required. NAVSEP was therefore modified by the following during the ejector stroke:

For 0.0 < t<.030

$P = (\Delta C_l = \sin\phi * F_{EJ} * \text{store radius}) * FACT11$

$Q = \{F_{Z1} * (X_{CG} - X_1) + F_{Z2} * (X_2 - X_{CG})\} * FACT21$

$R = \{F_{Z1} * (X_{CG} - X_1) + F_{Z2} * (X_2 - X_{CG})\} * FACT31$

For 0.03 < t<.045

$P = (\Delta C_l = \sin\phi * F_{EJ} * \text{store radius}) * FACT12$

$Q = \{F_{Z1} * (X_{CG} - X_1) + F_{Z2} * (X_2 - X_{CG})\} * FACT22$

$R = \{F_{Z1} * (X_{CG} - X_1) + F_{Z2} * (X_2 - X_{CG})\} * FACT32$

A considerable improvement in the yaw and roll rates for the first 0.09 seconds were achieved for the first flight, Figure 4.

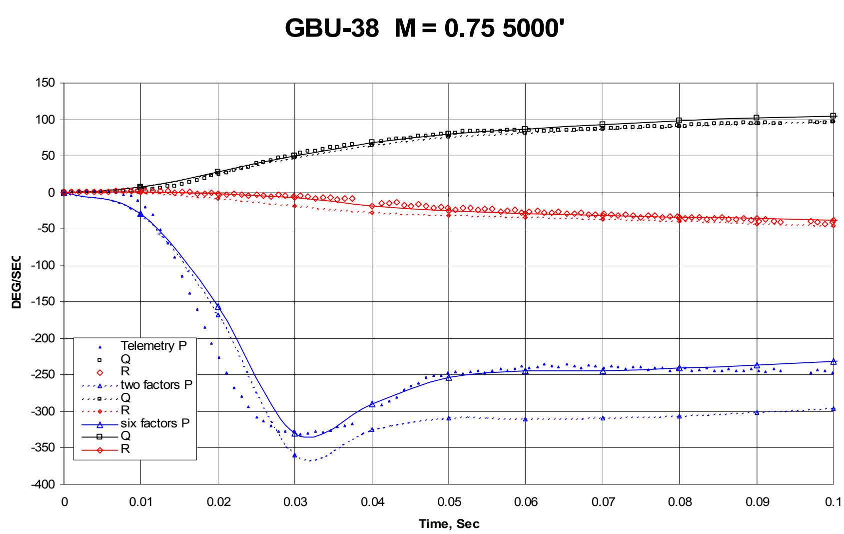

Figure 4

Ideally, a combined aeroelastic/structural model of the BRU-55 ejector and MK-82 JDAM during the ejector stroke could be developed. A calculation of the effects of ejector force dynamics during the ejector stroke would provide the best solution to modeling the store's inertial response. However, this approach was beyond the scope of the program.

3.0 Residual Calculations

The Residual was defined as:

$$\textbf{Residual} = \{(P_T-P_P)^2/P_T^2+(Q_T-Q_P)^2/Q_T^2+(R_T-R_P)^2/R_T^2\}^{1/2}$$

(where the subscript T (True) referrers to flight test data and P (Prediction) to NAVMOD predictions)

3.1 Subsonic Residual

As is shown in Figure 5, the roll factor is the only one that has a significant value for time 0<.03, while the pitch and yaw factors show large oscillations around zero, as the residual is gradually reduced. The roll factor for the first time increments are substantially larger than for the other two. This is to be anticipated, since the roll effect is expected to be substantially larger than that for pitch or yaw, which are secondary effects. However, for the second time increment, both the yaw and roll tend towards a constant value with a reduction in residual, Figure 6. Note that the roll factor changes sign from the first to second time interval.

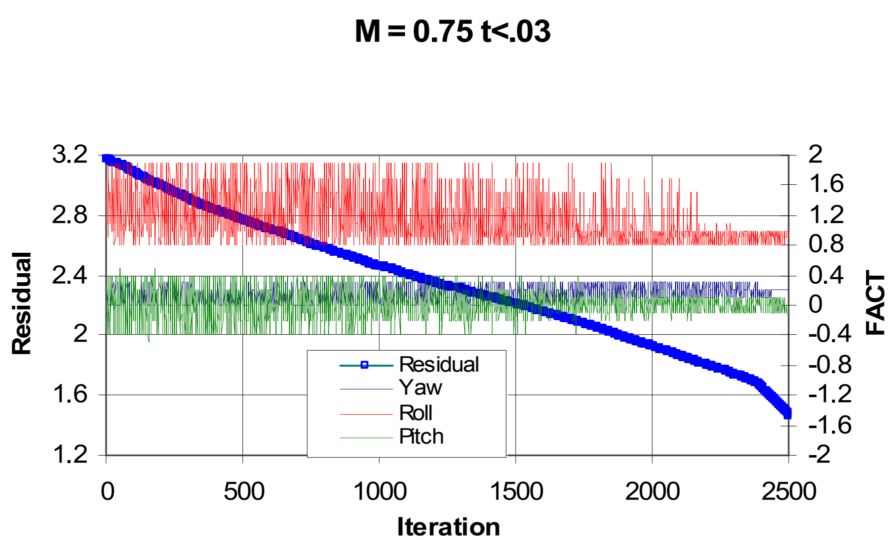

Figure 5

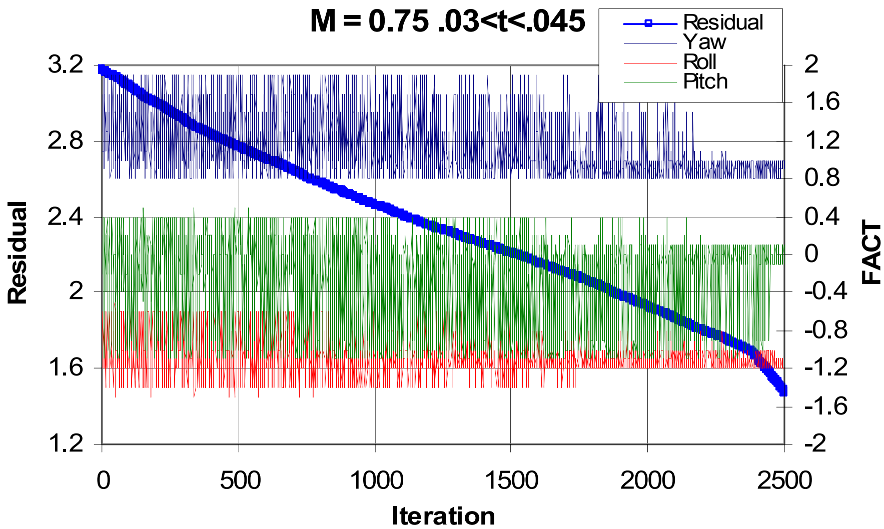

Figure 6

3.2 Transonic Residuals

The pitch residuals for the same configuration are shown in Figures 7A and 7B. Note that the pitch factor is zero for all three Mach numbers for the first time interval. For the second time interval, the pitch factor seems to converge to about –1 for the transonic case, but is still zero for the subsonic case.

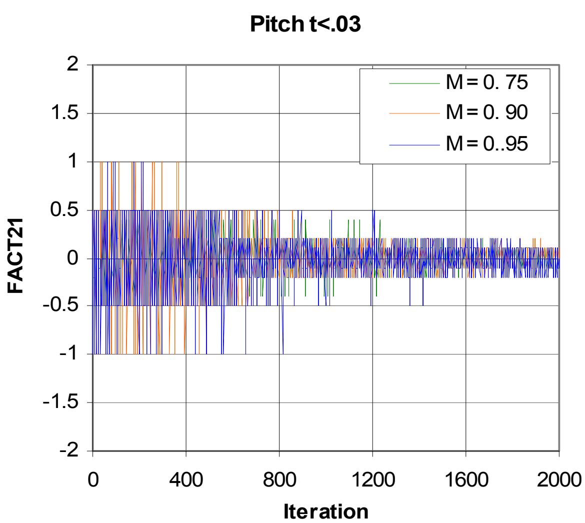

Figure 7A

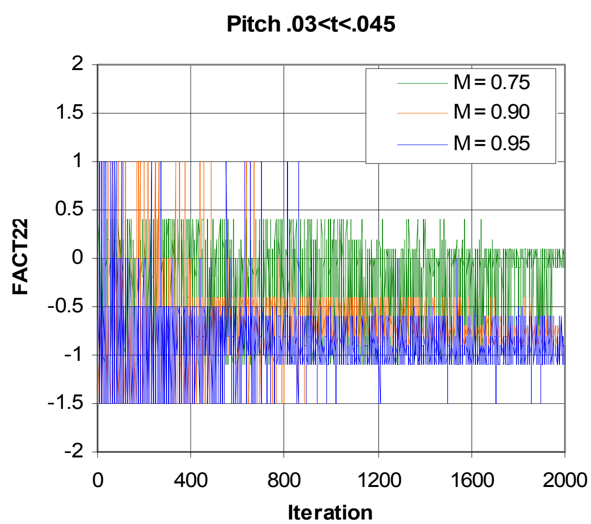

Figure 7B

The yaw factors are shown in Figures 8A and 8B. Note that for the first time interval, the yaw factors converge to a small positive value less than one, while for the second time interval the yaw factors show considerable variation, and are much higher for the transonic Mach number.

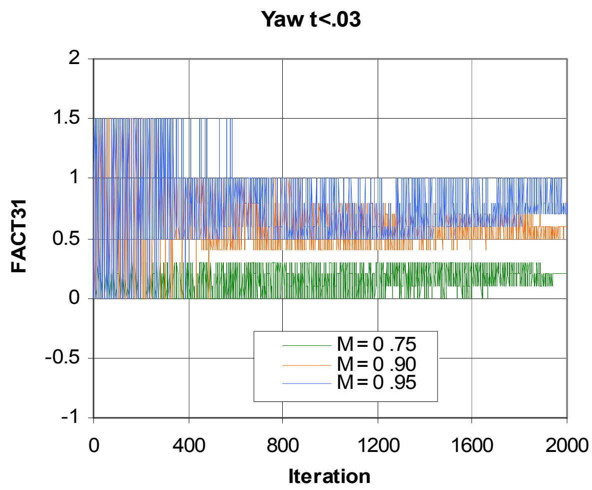

Figure 8A

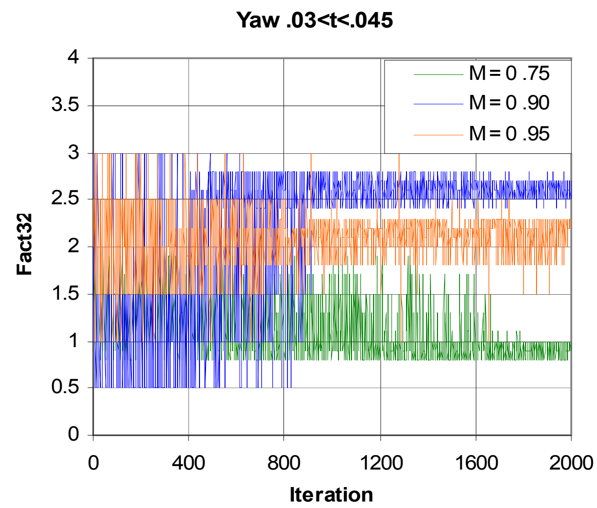

Figure 8B

The roll factors are shown in Figures 9Aand 9B. The roll factors converge to a value of approximately 2 for the first time interval, and between –1 and –1.6 for the second time interval.

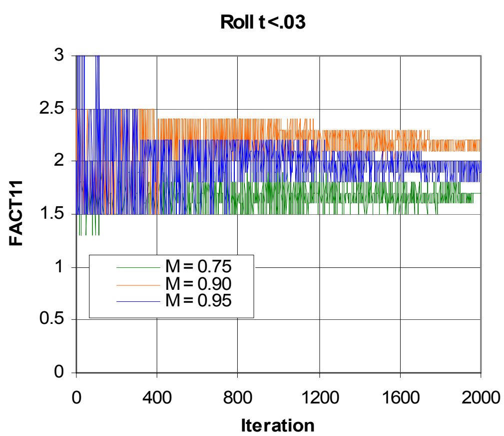

Figure 9A

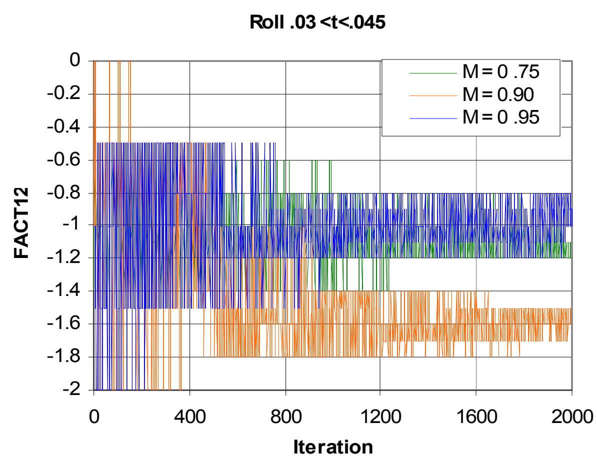

Figure 9B

The premise for developing a set of factors was to improve the store trajectory simulation capability. Since the factors seem to vary with Mach number, it seems that the technique is not particularly useful, since it couldn't be used with confidence for a Mach number not tested.

The residual for the three flights is shown in Figure 10. Note that the subsonic residual is much smaller, and substantially different from that at the two transonic Mach numbers. It must be realized that the two transonic flights were conducted at the same higher airspeed.

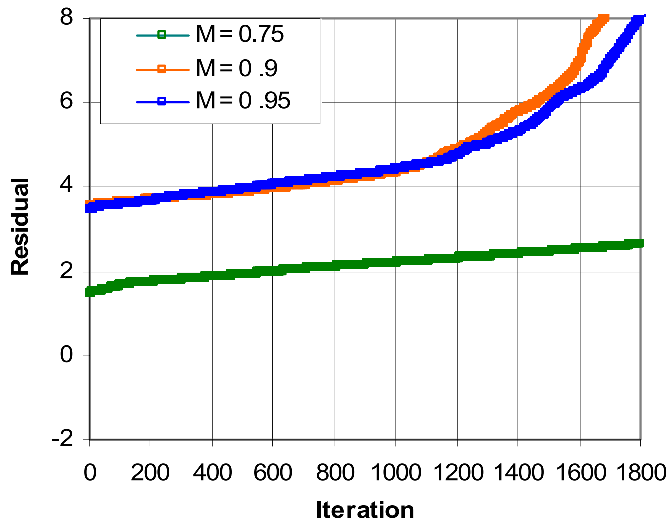

Figure 10

Since store trajectories are a function of aerodynamic coefficients which are multiplied by the dynamic pressure, it's clear that ejector force vibration effects will also be influenced by the true airspeed. As may be seen in Figures 7 through 9, the transonic factors seem to converge to the same value.

Ideally, transonic factors would be available from the first flight. However, that is usually not the case since the Navy uses a build-up technique in their flight test program. However, as may be seen in Figure 11, the trajectory prediction was considerably improved at M = 0.96 using the factors obtained at M = 0.75.

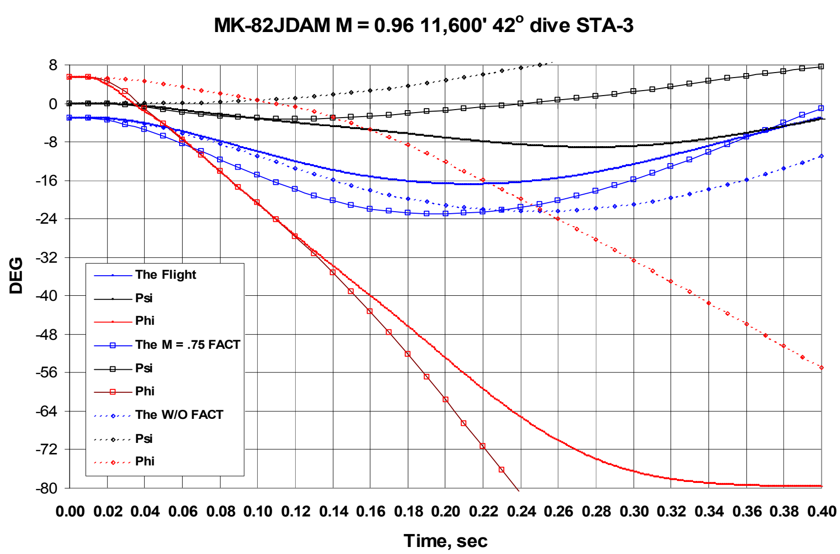

Figure 11

This technique was used throughout the GBU-38 flight test program with great success.

3.3 GBU-32

For the GBU-32 (1000# JDAM) first flight test point the GBU-38 (500# JDAM) roll factors were adjusted by using the different bomb radius. As may be seen in Figure 12, an excellent match with the flight test data was achieved. Note that the 1000# bomb roll effect due to the ejector is considerably less than that for the 500# variant.

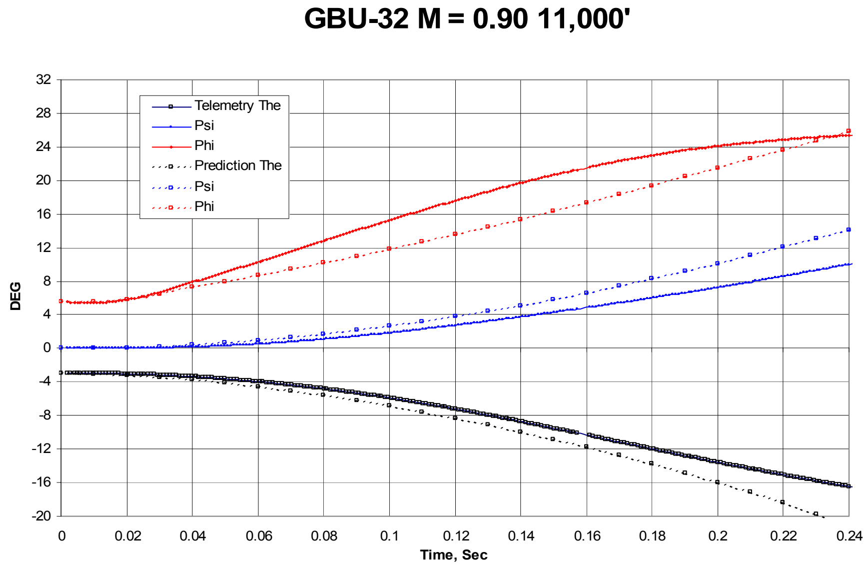

Figure 12

Although developing GBU-32 factors gave a better match for this case, using the GBU-38 factors for the first flight gave an excellent pre-flight prediction.

4.0 Conclusions

Flight test telemetry data have considerably improved the Navy's capability of Modeling and Simulation of store trajectories. Pitch, yaw and roll rates during the ejector stroke allow for the modeling of inertia effects that appear to be invariant with Mach number, and can be used for predictions for future flights.

The Navy has long advocated[3,4] the use of grid, rather than CTS trajectory, wind tunnel testing. For the F-18/ GBU-38 program the wind tunnel CTS trajectories were useless. When the NAVSEP program was modified to take account of ejector effects on the rack, an excellent match with flight test data was achieved. The advantages of using grid data in conjunction with M&S during the flight test program have been clearly demonstrated.

Clearly, stores dropped from BRU-55's may be imparted a sizable rolling moment which has to be accounted for, both in the wind tunnel and the M&S before flight test. The excellent match between the NAVMOD program and the flight test results enabled the elimination of two flights and four store assets (from the original planned 18 flights and 28 stores), at a considerable cost saving to the program. If only CTS data had been taken during the wind tunnel entry not only would the program's success have been jeopardized, but the improvement in M&S tools would not have been possible.

Ideally, a combined aeroelastic/structural model of the BRU-55 ejector and GBU-38 during the ejector stroke could be developed. A calculation of the effects of ejector force dynamics during the ejector stroke would provide the best solution to modeling the store's inertial response. However, this approach could not be adopted in the middle of a flight test program.

The GBU-38 program was successfully completed. The flight test for the GBU-32 from the BRU-55 on the F/A-18C was also successfully completed. A similar approach to M&S using telemetry data was used. The Navy's M&S has been considerably improved, since the effects of store weight, inertia and ejector forces can be properly determined.

5.0 References

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DISCUSSION EDITING

Paper No. 13: Stores Use of Statistical Tools to Improve Modeling and Simulation of Store Separation

Authors: A.Cenko,A.Piranian

Speaker: Al Piranian

Discussor: G.W. Foster

Question: Does the author think wind-tunnel + CFD methods can give a flight clearance (without flight tests) at least for emergency jettison.?

Speaker's Reply: Emergency jettison, where all the stores are simultaneously released, usually at take-off or landing, can only be done by simulation due to the low speeds involved. To the best of my knowledge the only store that might have caused problems was the BQM-134, which was a UAV with a fairly large wing. This store was never flown, since the program was cancelled.

Discussor: M. Tutty

Question: Al, has this technique been used in subsequent test programs as yet?

Has the experience in the use of NAVMOD obviated the need for 6DOF TM packs in stores as yet?

Speaker's Reply: 1. It is expected to be used for F-18 E/F stores separation analysis and test.

2. 6 DOF TM kits are still the best means of measuring what the store is doing. Using predictions of store angular rates (based on wind tunnel input data) and comparing, real-time, with the flight test measured rates, allows the test engineer to conduct multiple separations, in a single flight, while expanding the jettison/ employment flight envelope.

Photogrammetrics is an aircraft reference instrumentation system which provides the best measure of store/ aircraft miss distance, but is not a preferred source for providing store-alone dynamics.

Discussor: A.Cunningham

Question: Did you evaluate the effects of store mass properties variations /within tolerances) on the coefficients that you derived for your simulation?

Speaker's Reply: We used the actual mass properties in determining the factors. Since the mass properties are measured before every flight, their effects would be properly modelled.